ANALYSIS OF THE INFLUENCE OF THE OGE/IGE TRANSITION ON VAK-191B FLYING QUALITIES IN HOVER

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Introduction

The VAK-191B program made extensive use of a ground-based hover test rig which allowed full scale power-on testing of the hover characteristics of the airplane (reference (a)). The rig or pedestal is fixed to the ground which prevents longitudinal and lateral translation; rotation about all aircraft axes and limited vertical travel are provided. The frequency response data obtained with the aircraft installed in this rig are the basis for this IGE (in ground effect) analysis of the VAK-191B. The limited vertical travel of the pedestal was not sufficient to test the aircraft OGE (out of ground effect) so that equivalent OGE pedestal frequency response data are not available.

Single axis pitch and roll frequency response data were taken with the VAK-191B control system in the VTOL mode. This mode has proportional attitude command in each axis. Therefore, while the pitch axis input command was oscillated, the roll control system attempted to hold wings level and, similarly, while the roll axis input command was oscillated, the pitch control system attempted to maintain a reference attitude. The yaw axis of the pedestal was locked for these tests because the aircraft yaw control system is rate command in all modes and would allow aircraft heading to drift in the presence of yaw moment disturbances.

Analysis of the roll response data which produced quantification of the IGE propulsion-induced roll angle effect on the aircraft and subsequent analysis of the influence of this effect on roll flying qualities are described. Validity of the analytical flying qualities results and the IGE and OGE roll models is established by comparison with VAK-191B operational limitations and pilot comments on the aircraft's handling characteristics. A similar analysis of the pitch response data was made and figures summarizing these results are included in the Appendix to this paper.

Frequency Response Analysis

Figure 1 is a functional diagram of the VTOL mode of the VAK-191B roll flight control system. (Control system details are given in reference (a).) In this mode lateral motion of the cockpit control stick commands roll attitude (ϕ_c) proportional to stick deflection. The system is fully fly-by-wire with no limiting of feedback authority. The transfer relation between aircraft roll angle (ϕ) and roll moment (M_{c_F}) inputs is designated "pedestal/aircraft roll dynamics" because of the inability to isolate pedestal and aircraft dynamic responses from the frequency response data.

The intent of the frequency response analysis was to seek correlation between VFW-Fokker control system background data and the measured pedestal

data. Since the characteristics of all elements in figure 1 except the pedestal/airframe roll dynamics could be and were determined with a high degree of confidence in laboratory situations, the first step in the analysis was to establish a model for the pedestal/airframe roll dynamics. (Note that since M_{C_r} is proportional to duplex servo output (δ_{DS}) and M_{C_r} is not measurable, pedestal/airframe dynamics can also be represented as ϕ/δ_{DS}.) This was accomplished as follows:

1. A frequency response for the ϕ to δ_{DS} transfer characteristics was determined from the pedestal data (see data points on figure 3). It was observed on the time traces that the ϕ and δ_{DS} waveforms were only slightly distorted from pure sinusoids; this indicated that a linear model could reasonably represent the ϕ to δ_{DS} transfer characteristics.

2. Since the aircraft is IGE when installed on the pedestal, the fountain and flow entrainment characteristics depicted in figure 2 were examined. It is evident that an unstable propulsion-induced roll moment due to roll angle (L_ϕ) may be present; right wing down causes the fountain to move with respect to the aircraft in a direction which produces a right wing down moment; also the reduced clearance between right wing tip and the ground causes reduced pressure on the underside of the wing and a resultant right wing down moment. A roll moment due to roll rate (L_p) may also be present but could not be observed within the limits of the data as indicated by the next consideration.

3. The phase of the ϕ to δ_{DS} response determined in step 1 deviated only slightly from 180 degrees throughout the frequency range of the pedestal data (1.7 to 9.0 rad/sec) shown on figure 3. If an L_p were present, the phase would have deviated significantly from 180^0 through some frequency range; so it was concluded that the available data did not support the presence of L_p.

4. It is assumed herein that at zero airspeed (which the pedestal data represent) and OGE the ϕ to δ_{DS} transfer characteristics are

$$\left.\frac{\phi}{\delta_{DS}}\right|_{OGE} = \frac{K_{BS_r}}{I_x s^2} \qquad (1)$$

where s = Laplace variable

I_x = VAK-191B roll inertia = 3140 slug ft^2

K_{BS_r} = VAK-191B bleed system gain = 57.0 ft-lb/% δ_{DS}

This transfer function has 180^0 phase at all frequencies and thus matches the measured phase data. The measured gain data follow the $1/s^2$ trend at high frequencies but tend towards a finite D.C. value (figure 3). This deviation supports the presence of propulsion-induced effects IGE which are not present OGE.

5. After considering all the above observations it became evident that the ϕ to δ_{DS} dynamics could be represented by a second order system with ϕ feedback and no damping:

$$I_x\ddot{\phi} = K_{BS_r}\,\delta_{DS} + L_\phi\,\phi \qquad (2)$$

where L_ϕ is greater than zero and must be determined

6. Fitting the pedestal data with various L_ϕ's resulted in L_ϕ = 450 ft-lb/deg and the following ϕ to δ_{DS} transfer function:

$$\frac{\phi}{\delta_{DS}} = \frac{-0.114}{(-0.35s+1)(0.35s+1)} \qquad (3)$$

Figure 3 demonstrates the excellent fit accorded by this relatively simple model.

The second step in the frequency response analysis was to calculate the closed loop ϕ/ϕ_c characteristics and compare them with the measured characteristics. OGE and IGE ϕ/ϕ_c frequency responses were calculated using equations (1) and (3), respectively, with the transfer functions given in figure 1 for the remaining loop elements. The results are shown in figure 4. Note that there is a significant difference between OGE and IGE characteristics. Note also that the calculated IGE characteristics provide an excellent match of the measured magnitudes and a good match of the measured phases. An excellent phase match is obtained if a 0.06 dead time between ϕ and ϕ_c is assumed; this is not an unreasonable assumption in view of the fact that the actual frequency response was determined from strip chart data.

Summarizing the VAK-191B roll axis frequency response analysis supports the use of a simple second order model with no rate feedback and unstable attitude feedback (equation (2)) to represent the IGE roll dynamics (more specifically the pedestal/aircraft dynamics) of the unaugmented airplane. The significant differences between IGE and OGE dynamics can now be examined in terms of the roll flying qualities changes which occur in the OGE to IGE transition and vice versa.

Model for IGE/OGE Flying Qualities Analysis

Figure 5 is a model for manual control of the lateral position of the VAK-191B in hover. This model was analyzed to quantify the changes in system dynamics, pilot compensation, and control power usage which occur in the OGE/IGE transition. The VAK-191B roll attitude control system detailed in figure 1 was given the equivalent form shown in figure 5 by neglecting the high frequency duplex servo dynamics, combining the roll angle and roll rate feedback paths, neglecting the stick shaping network dynamics because of the near cancellation of the pole and zero, and inserting the IGE and OGE representations for the unaugmented airplane established by the frequency response analysis. A disturbance roll moment (L_{DIST}) was included to represent random roll moment inputs which arise from sources such as atmospheric or ship airwake turbulence or control cross-coupling. The displayed information (ΔY) represents the information required by the pilot to maintain lateral position;

this information may be obtained by viewing the outside world or a cockpit display. Note that lateral acceleration is proportional to roll attitude in hover and the lateral position (Y) to ϕ dynamics can be represented as a K/s^2.

Controlled Element Changes

The controlled element (i.e., that controlled by the pilot) in figure 5 is the VAK-191B with its ϕ to ϕ_c and $\dot{\phi}$ to ϕ_c control loops closed. A root locus comparison of these loop closures OGE and IGE is given by figure 6. Since the control system characteristics do not change in transitioning between OGE and IGE the loops are closed with the same root locus gain. The effect of the unstable roll angle feedback IGE is to move the open loop airframe poles from the origin OGE to $\sigma = \pm 2.86$ rad/sec IGE. This in turn causes a significant change in the controlled element root locus and the ϕ/ϕ_c closed loop roots; the dominant roots move from $\zeta = 0.87$, $\omega_n = 2.75$ rad/sec OGE to $\zeta = 0.58$, $\omega_n = 0.34$ rad/sec IGE. In transfer function format, the OGE and IGE ϕ/ϕ_c dynamics are as follows:

$$\left(\frac{\phi}{\phi_c}\right)_{OGE} = \frac{9.51(s+0.44)}{(s+0.55)[s^2+2(0.87)(2.75)s+2.75^2]} \tag{4}$$

$$\left(\frac{\phi}{\phi_c}\right)_{IGE} = \frac{9.51(s+0.44)}{(s+4.93)[s^2+2(0.58)(0.34)s+0.34^2]} \tag{5}$$

Equations (4) and (5) define the controlled element OGE and IGE respectively.

Pilot Compensation Considerations

POR (Pilot Opinion Rating) is correlated with the degree of compensation that must be effected by a pilot to perform a given task with a specific controlled element according to the following principle: the more gain, lead, or higher order compensation required by the pilot, the higher will be the POR and the poorer will be the flying qualities of the controlled element. The change in pilot compensation (ΔY_{p_R}) required to maintain constant lateral positioning performance when transitioning from OGE to IGE is given by:

$$\Delta Y_{p_R} = \frac{(\phi/\phi_c)_{OGE}}{(\phi/\phi_c)_{IGE}} = \frac{(s+4.93)[s^2+2(0.58)(0.34)s+0.34^2]}{(s+0.55)[s^2+2(0.87)(2.75)s+2.75^2]} \tag{6}$$

This assumes that the pilot provides compensation when entering ground effect which will maintain a constant $Y/\Delta Y$ transfer function (see figure 5) or, equivalently, constant Y/Y_c closed loop performance.

The frequency response of ΔY_{p_R} is plotted in figure 7. The response indicates that the pilot must reduce his OGE gain by a factor of 10 and produce a second order lead in order to maintain constant lateral positioning performance IGE. These required compensation changes support the conclusion that the VAK-191B exhibits degraded lateral flying qualities upon transitioning from OGE to IGE.

The U.S. Marine Corps pilot for the VAK-191B flight test program records in reference (a) the following observations concerning the aircraft's lateral flying qualities:

1. In hover OGE a PIO (Pilot Induced Oscillation) could be produced by trying to maintain tight control of lateral position.

2. The technique adopted for vertical landing was to establish a hover OGE over the desired landing spot and let down without correcting for lateral drift.

The second observation which indicates pilot reluctance to enter the loop (i.e., he adopts a low gain) while IGE is partially supported by the ΔY_{p_R} analysis which indicated a large reduction in pilot gain required for IGE conditions. Both observations can be fully appreciated by referring to figure 8 which depicts root loci of the manual Y to Y_e loop closures both in and out of ground effect.

The inclusion of the Y/ϕ and ϕ/ϕ_c poles and zeros on the root loci is obvious; the inclusion of the zero at $\sigma = -1/\tau_L$ is not obvious. It can be shown (reference (b)) that an effective outer guidance loop closure can be obtained by simply feeding back position and position rate for systems meeting the following criteria:

1. Acceleration control is obtained by attitude

2. The attitude control bandwidth is wider than the guidance loop bandwidth.

3. Control coupling and dynamic coupling among the various degrees of freedom have been minimized by inner loops.

The lateral position control of a V/STOL airplane in general and the VAK-191B OGE in particular meets these criteria, therefore the zero has been added to figure 8 to show the position plus position rate feedback. This lead may be pilot-generated or generated by display "quickening". The lead has been arbitrarily placed to the left of the ϕ/ϕ_c pole at $\sigma = -0.55$ rad/sec on the OGE root locus and, similarly, to the left of the ϕ/ϕ_c zero at $\sigma = -0.44$ rad/sec on the IGE root locus.

Recall the first pilot observation while considering the OGE root locus in figure 8. The locus high gain asymptotes are such that the system can exhibit instability (i.e., PIO) if the pilot gain becomes too high. With $1/\tau_L$ assumed equal to 0.75 rad/sec the locus enters the right half plane (becomes unstable) at $j\omega = 2.14$ rad/sec with a pilot gain of 3.06 deg/ft. If the pilot becomes aggressive and increases his lead to $1/\tau_L = 0.20$ rad/sec, the character of the locus changes and the system becomes unstable at $j\omega = 2.68$ rad/sec with a pilot gain of 1.30 deg/ft. The locus changes in that the branches originating at the ϕ/ϕ_c oscillatory poles do not coalesce at the σ axis but drift towards the right half plane and define the stability of the system. The fact that the lateral position loop can go unstable and does so at a lower gain under conditions of increased pilot aggressiveness supports the pilot observation that he could produce PIO by trying to maintain tight lateral position control.

The IGE locus indicates that the lateral position loop becomes unstable at an extremely low gain and frequency (specifically, $j\omega$ = .03 rad/sec, and pilot gain = 0.0016 deg/ft) and does not regain stability. This means that any half-hearted attempt by the pilot to close the loop would result in PIO which supports the second pilot observation that he did not correct for lateral drift IGE.

Roll Control Power Considerations

The IGE and OGE lateral control models (figure 5) were compared on the basis of control power required for maneuvering, regulation of random disturbances, and trimming in a crosswind. Maneuvering control power was determined (see figure 9 for the equations) by calculating the magnitude of a step input in L_c which would produce 6 degrees of roll angle in 1 sec. This requirement was taken from the Navy Type A V/STOL Request for Information specification. Control power required for controlling random disturbances was obtained (see figure 9 for the equations) by assuming a form for the power spectral density of L_{DIST} ($\Phi_{L_{DIST}}$) and then calculating the RMS L_c ($\overline{L_c^2}$) required as a function of the standard deviation of L_{DIST} ($\sigma_{L_{DIST}}$) and the input spectrum bandwidth (ω_j). Control power required for trimming in a crosswind was determined (see figure 10 for the equations) by calculating the roll angle required to trim (ϕ_{TRIM}) a sideforce (Y_{CW}) due to a side velocity (v_{CW}) then calculating the control power required to trim the roll moment ($I_x\dot{\phi}_{CW}$) due to the same side velocity.

Control powers for maneuvering and controlling disturbances are compared on figure 11. The first shows normalized control power (i.e., roll acceleration) for OGE and IGE as a function of ω_j and $\sigma_{\dot{\phi}_{DIST}} = \frac{\sigma_{L_{DIST}}}{I_x}$. The maximum available VAK-191B roll control power is included for reference. The OGE and IGE control powers for maneuvering are approximately the same with OGE being about 6% higher than IGE. There is a significant difference between the OGE and IGE control powers required for disturbance regulation, the ratio between IGE and OGE requirements varying from approximately 2.0 at high ω_j to 7.0 at low ω_j. This result when compared with available VAK-191B control power correlates with pilot comments (reference (a)) that in close proximity to the ground in any wind at all the cockpit indicator for available roll control power frequently indicated little if any left. The tie between pilot comment and analytic result is that the automatic portion of the VAK-191B roll control system has 100% authority and was using most of the control power for disturbance regulation leaving little for pilot inputs.

Control powers for trimming in a crosswind are compared on figure 10. The figure shows control power required to trim side acceleration due to a side gust as a function of side acceleration (or equivalently ϕ_{TRIM}) and roll acceleration due to the same gust. Implicit in this presentation is a comparison of the effects of rolling moment due to sideslip (L_β) and side force due to sideslip (Y_β) on roll control power for constant side gust inputs. The effect of the propulsion-induced roll moment due to roll angle (L_ϕ) IGE is to couple the trim sideforce and roll equations. As can be seen, $L_\phi\phi_{TRIM}$ is a significant contributor which would use all available control power if ϕ_{TRIM} is greater than 12 to 15 degrees.

Conclusions

The analysis of the influence of OGE/IGE transition on VAK-191B lateral flying qualities in hover based on roll frequency response data taken in ground effect has resulted in the following conclusions:

1. An unstable propulsion-induced roll moment due to roll angle of approximately 450 ft-lb/deg is produced when the VAK-191B operates in ground effect. This effect is not present out of ground effect.

2. Good correlation with measured frequency response data was obtained with a simple model of the roll angle (ϕ) to duplex servo (δ_{DS}) dynamics of the VAK-191B.

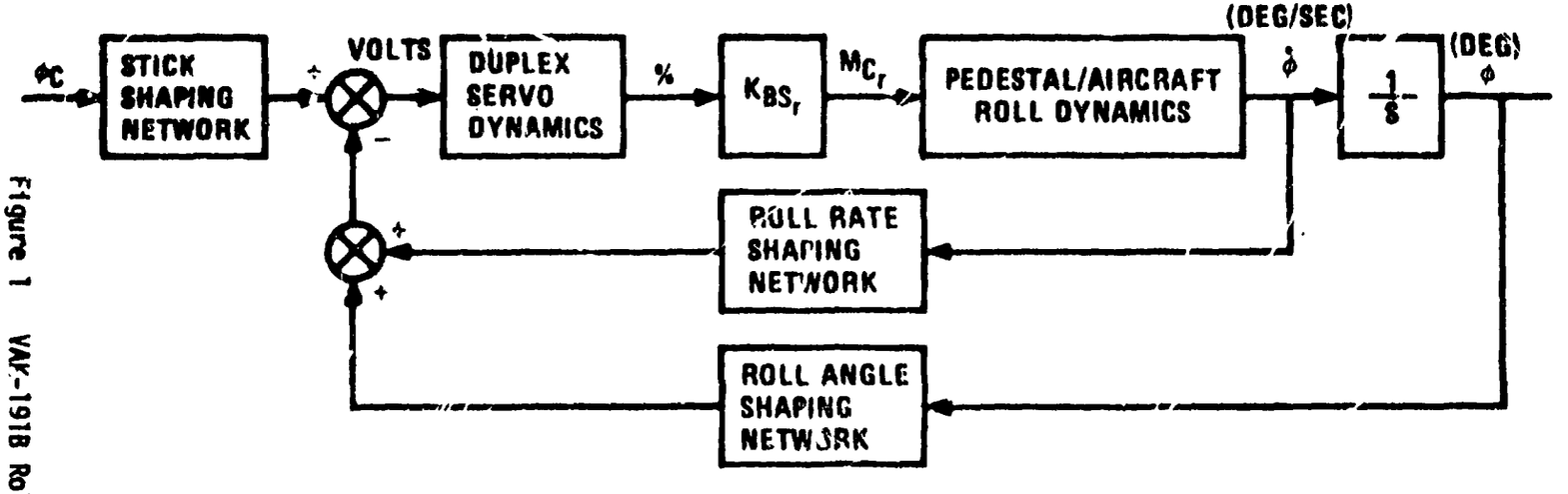
3. Results based on an analysis of a simple model for manual control of lateral position supported several observations of VAK-191B pilots concerning lateral flying qualities and indicated that trimming in a crosswind and regulating disturbances when in ground effect could easily require all available roll control power.

References

(a) VAK-191B Joint Flight Test Program Final Report, NAVAIRSYSCOM Report to be issued May 1977.

(b) Dukes, Theodore A., Helicopter Station Keeping, ECOM Technical Report 02412-9, September 1972.

VAK-191B ROLL CONTROL SYSTEM
VTOL MODE



G_{PA_r} = PEDESTAL/AIRCRAFT ROLL DYNAMICS

$= \frac{-0.114s}{(0.35s + 1)^1 (-0.35s + 1)}$ DEG/SEC/%

G_{ST_r} = STICK SHAPING NETWORK

$= \frac{0.88 (2.085s + 1)}{(2.29s + 1)}$ VOLTS/DEG

$G_{\dot{\theta}}$ = ROLL RATE SHAPING NETWORK

$= \frac{0.58 (1.8s + 1)}{(2.29s + 1)}$ VOLTS/DEG/SEC

G_{θ} = ROLL ANGLE SHAPING NETWORK

$= \frac{0.88 (1.8s + 1)}{(2.29s + 1)}$ VOLTS/DEG

G_{DS} = DUPLEX SERVO DYNAMICS

$= \frac{11.63}{\frac{s^2}{23.02^2} + \frac{2 (0.89)}{23.02} s + 1}$ %/VOLT

K_{BS_r} = 51.0 FT-LB/%

Figure 1 VAK-191B Roll Control System VTOL Mode

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YAK-191B FOUNTAIN CONFIGURATION
FRONT VIEW

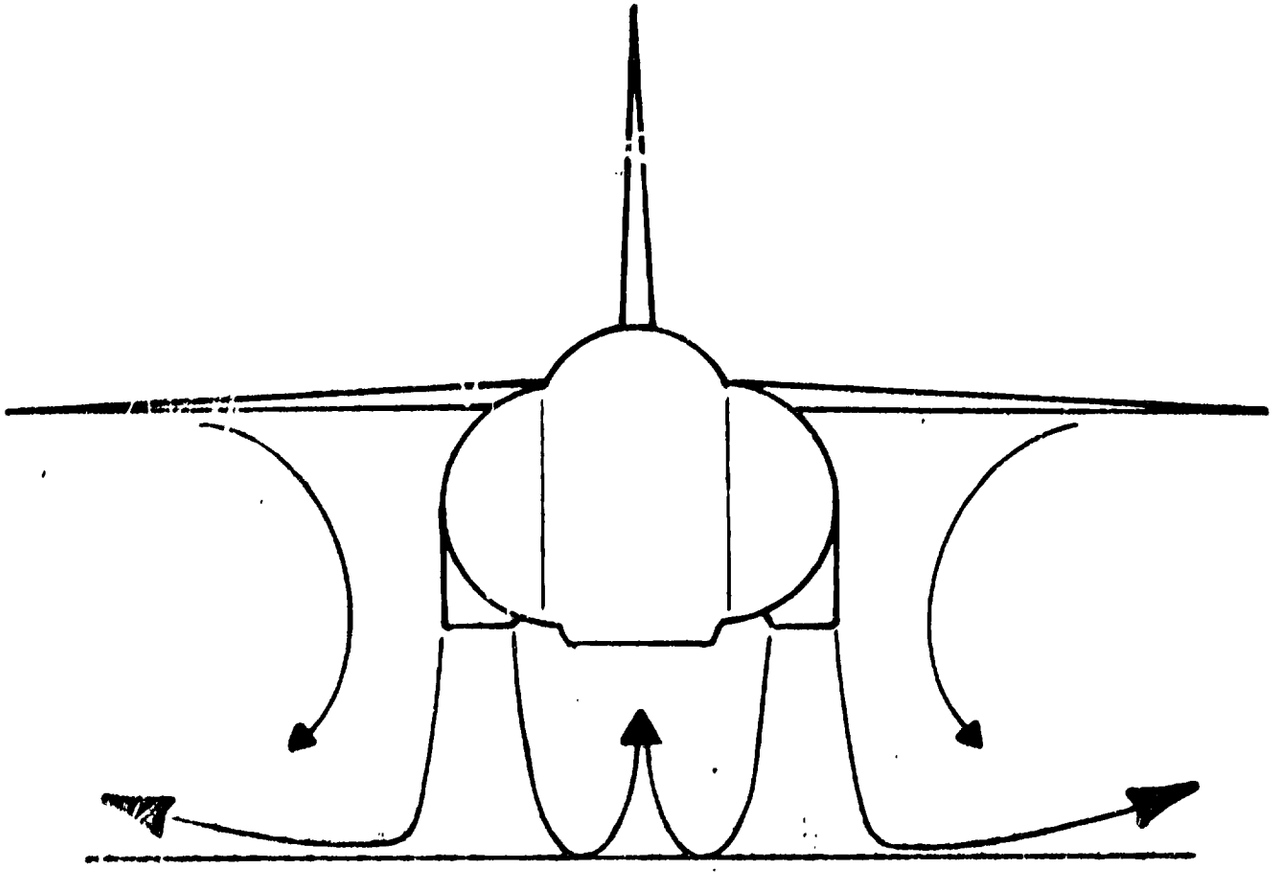


Figure 2 YAK-191B Fountain Configuration (Front View)

AIRCRAFT/PEDESTAL ϕ/δ_{DS} FREQUENCY RESPONSE

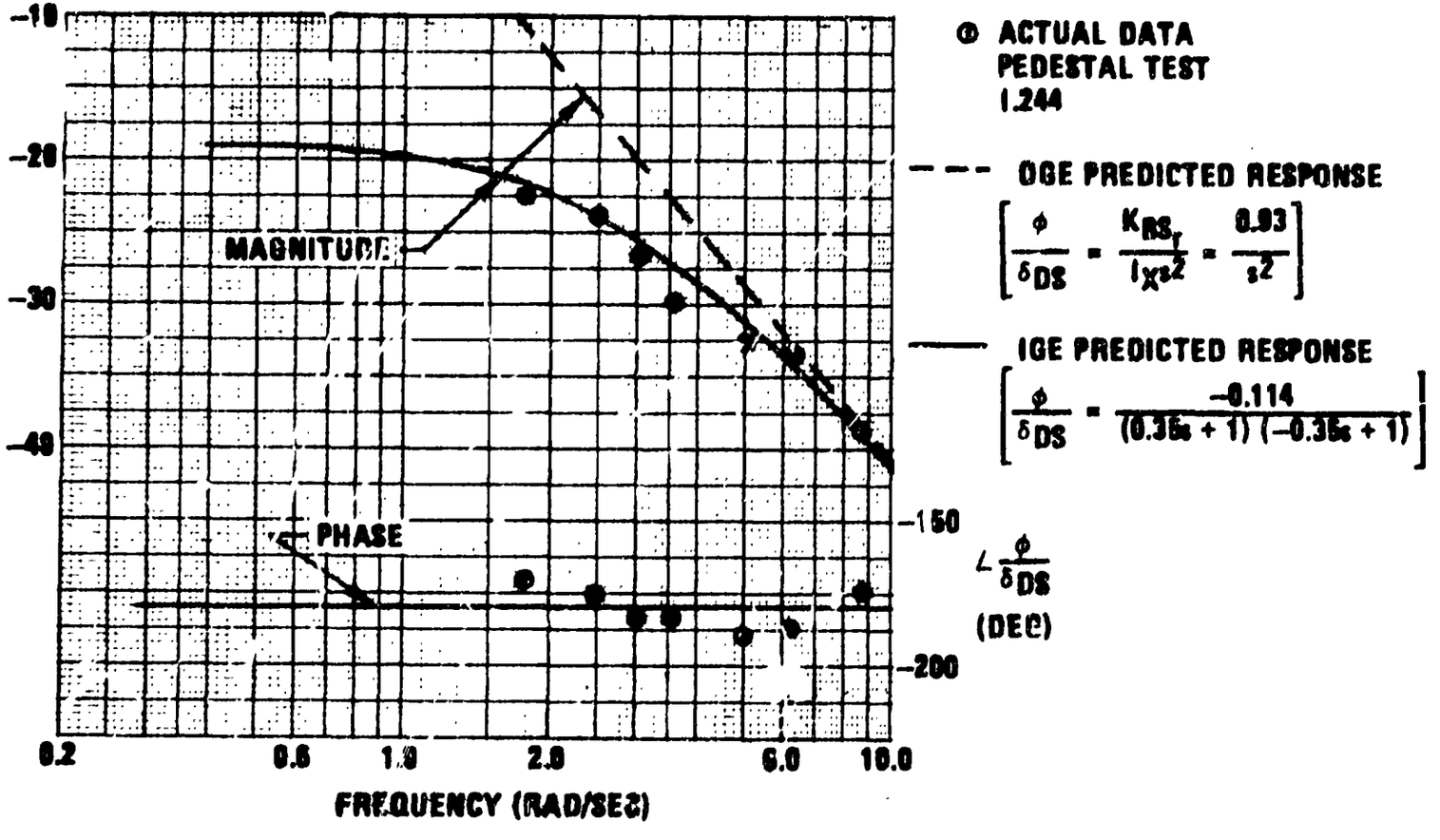


Figure 3 Aircraft/Pedestal ϕ/δ_{DS} Frequency Response

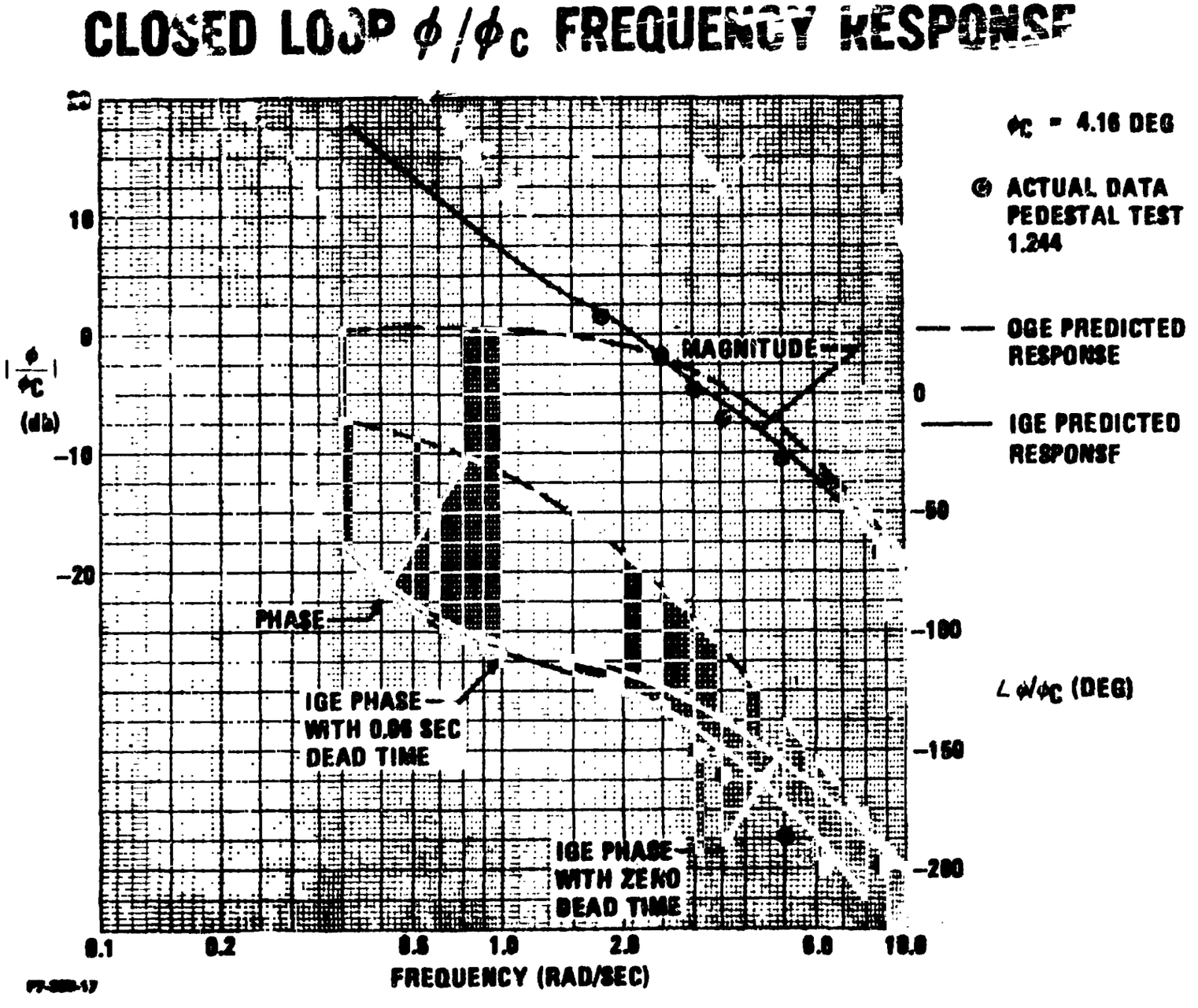
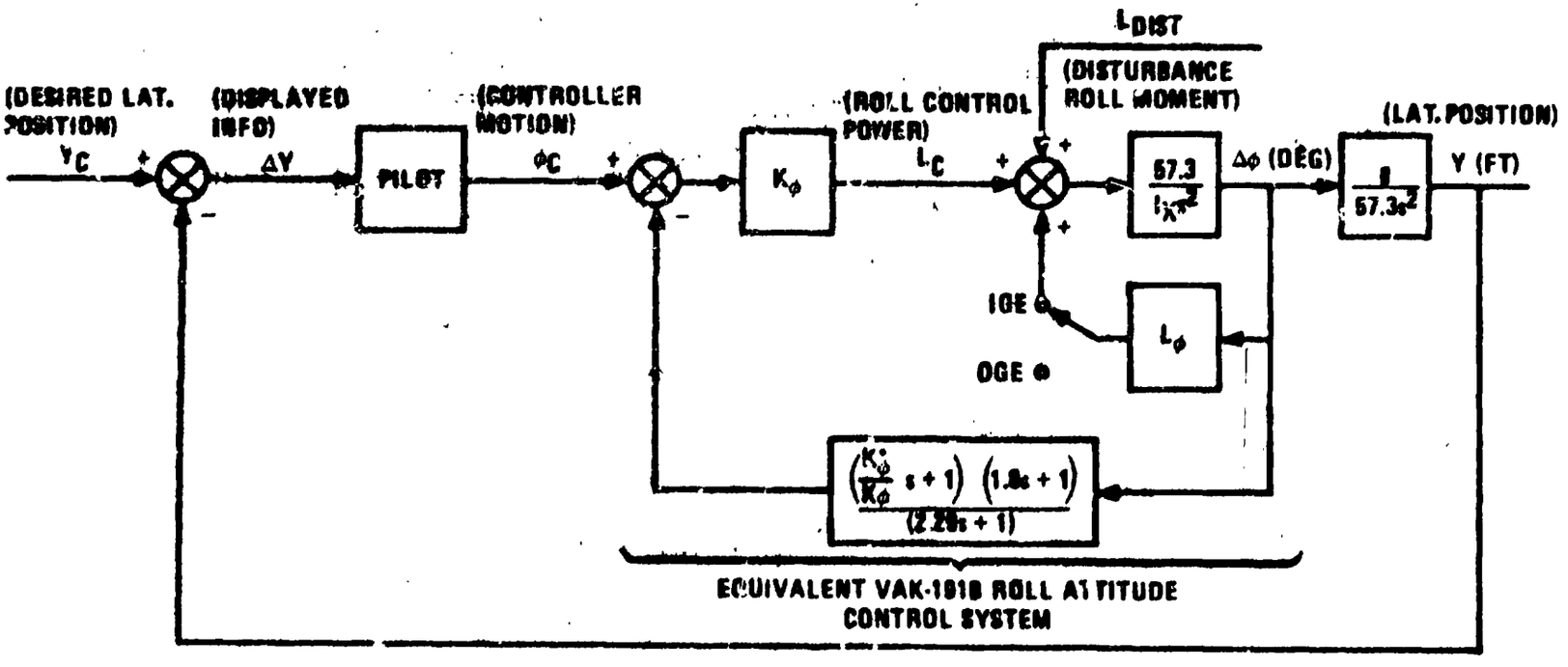


Figure 4 Closed Loop ϕ/ϕ_C Frequency Response

MODEL OF VAK-191B LATERAL POSITION CONTROL IN HOVER



CONTROL SYSTEM GAINS

K_ϕ = 521.3 FT-LB/DEG

$K_{\dot\phi}$ = 242.5 FT-LB/DEG/SEC

IGE FEEDBACK

L_ϕ = 450 FT-LB/DEG

I_X = 3140 SLUG-FT^2

Figure 5 Model of VAK-191B Lateral Position Control in Hover

DIFFERENCE IN VAK-191B CONTROLLED ELEMENT CHARACTERISTICS IN GROUND PROXIMITY

ROOT LOCUS COMPARISON OF ROLL ATTITUDE CONTROL

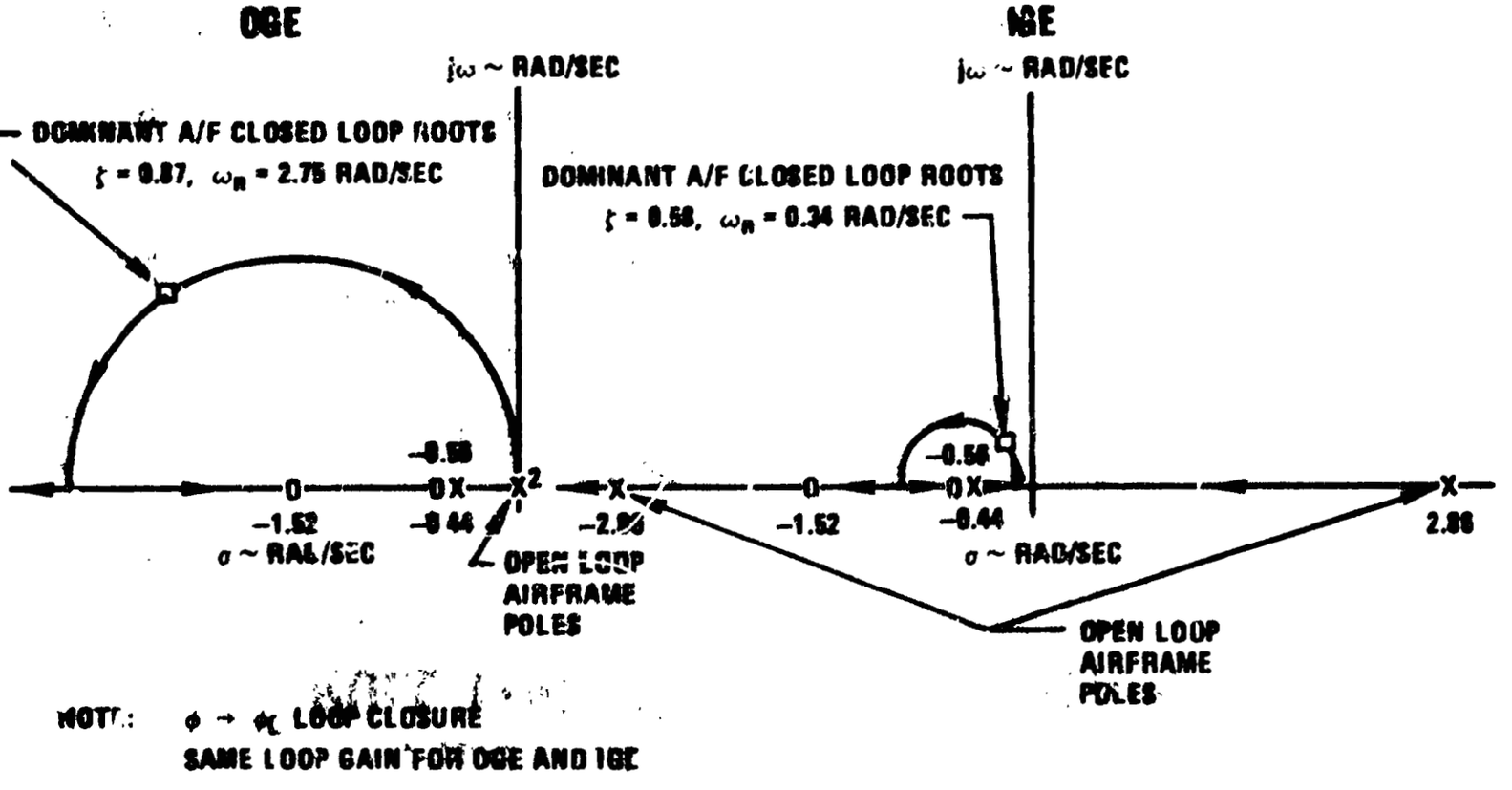
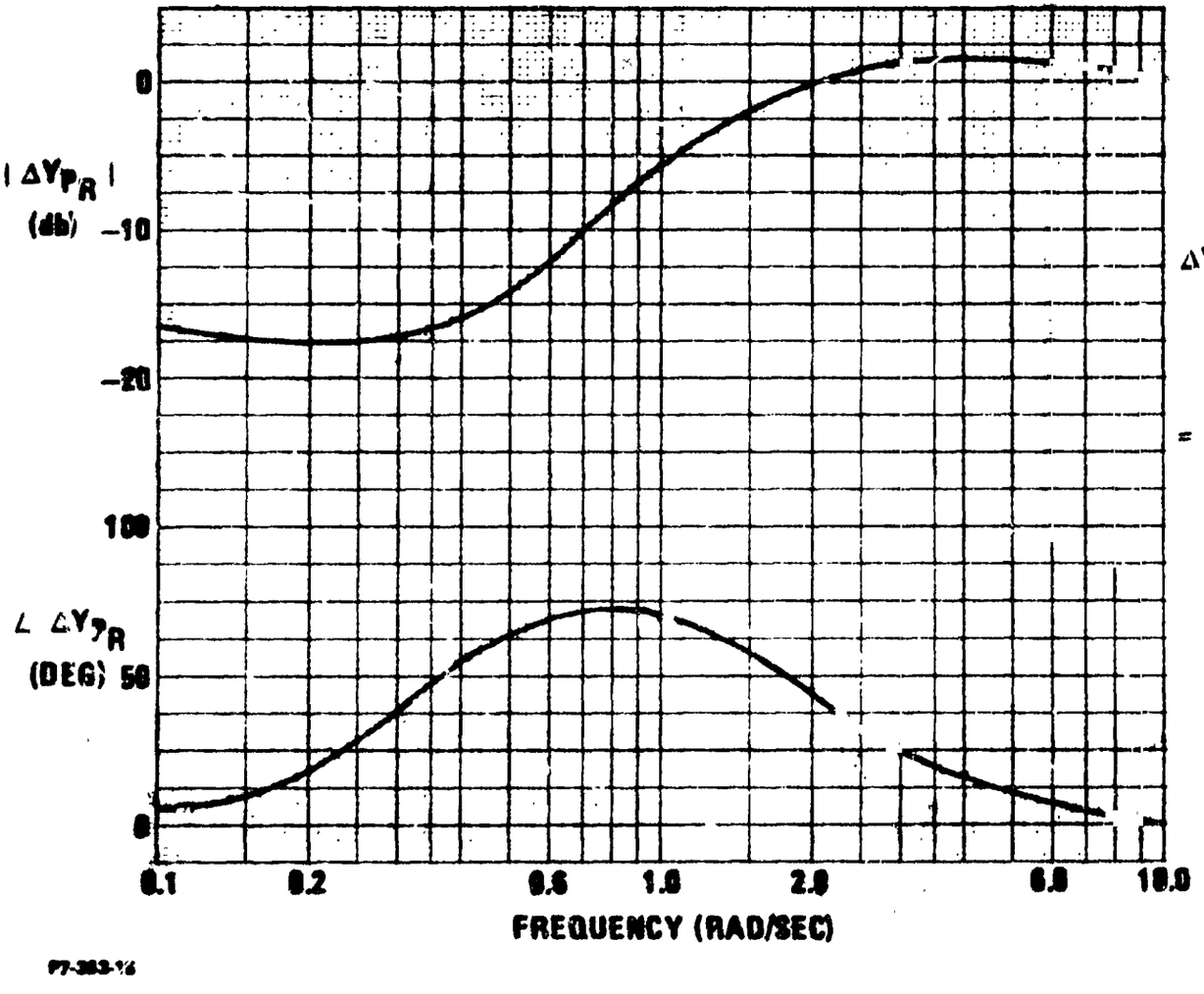


Figure 6 Difference in VAK-191B Controlled Element Characteristics in Ground Proximity - Root Locus Comparison of Roll Attitude Control

PILOT COMPENSATION IN ROLL FOR OGE/IGE TRANSITION



$$\Delta Y_{P_R} = \frac{\left(\frac{\phi}{\delta C}\right)_{OGE}}{\left(\frac{\phi}{\delta C}\right)_{IGE}}$$

= PILOT COMPENSATION REQUIRED FOR TRANSITIONING FROM OGE TO IGE TO MAINTAIN CONSTANT LATERAL POSITIONING PERFORMANCE

Figure 7 Pilot Compensation in Roll for OGE/IGE Transition

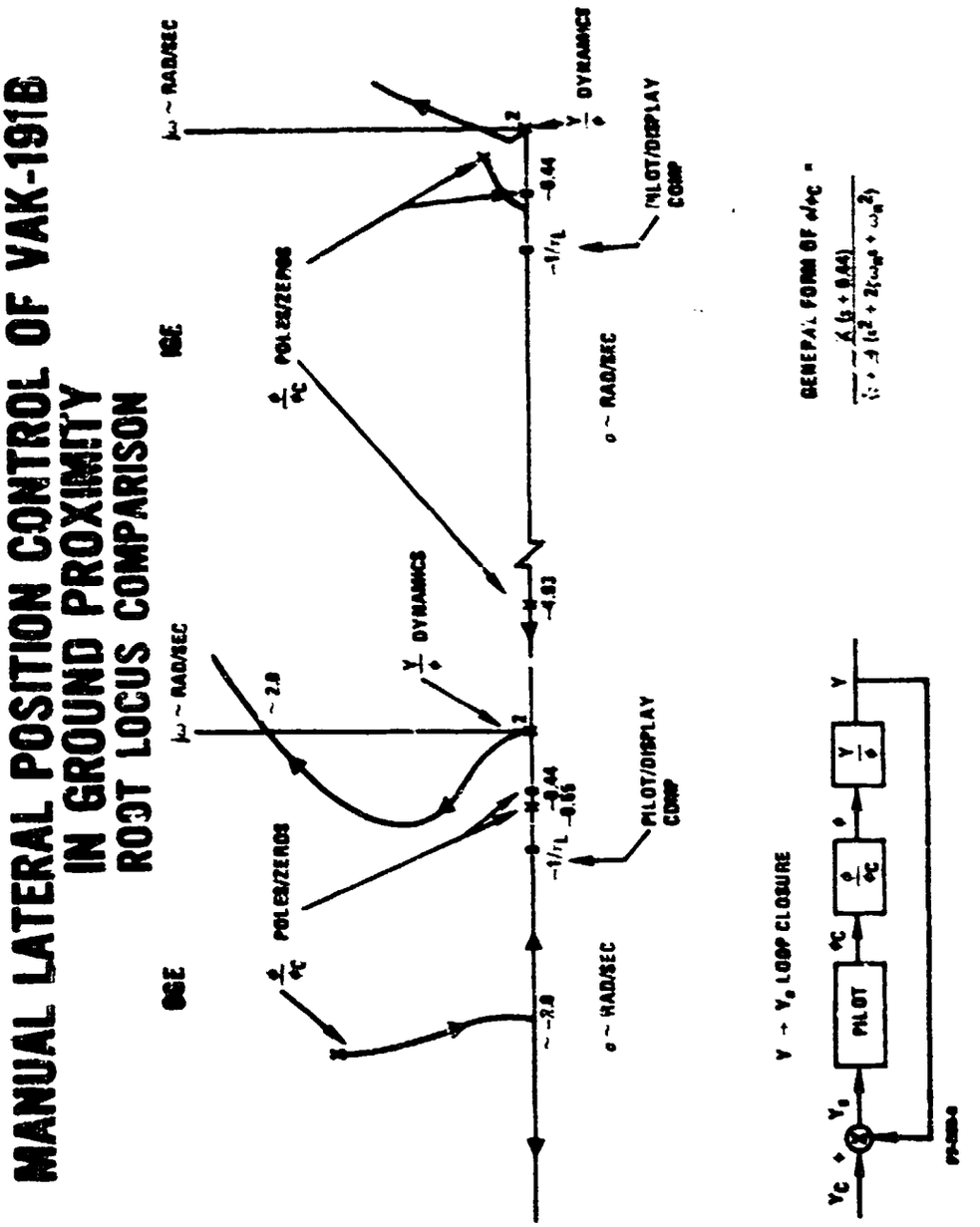


Figure 8 Manual Lateral Position Control of VAK-191B in Ground Proximity - Root Locus Comparison

ROLL CONTROL POWER EQUATIONS

C.P. FOR MANEUVERING

$$\frac{\phi}{L_C}(s) = \frac{0.0182\,(s + 0.44)}{(s + \alpha)\,(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad \text{(T.F.)}$$

$$L_C = \frac{L_{MAN}}{s} \quad \text{(INPUT)}$$

$$\phi(t) = L_{MAN}\,\mathcal{L}^{-1}\left[\frac{1}{s}\,\frac{\phi}{L_C}(s)\right]$$

$$L_{MAN} = \phi(1)/\left[\mathcal{L}^{-1}\left[\frac{1}{s}\,\frac{\phi}{L_C}(s)\right]\right]_{t=1}$$

$$\alpha = \begin{cases} 0.55 & \text{OGE} \\ 4.93 & \text{IGE} \end{cases}$$

$$\omega_n = \begin{cases} 2.75 & \text{OGE} \\ 0.34 & \text{IGE} \end{cases}$$

$$\zeta = \begin{cases} 0.87 & \text{OGE} \\ 0.58 & \text{IGE} \end{cases}$$

C.P. FOR CONTROLLING DISTURBANCES

$$\frac{L_C}{L_{DIST}}(s) = \frac{4.90\,(s + 0.56)\,(s + K_\phi/K_{\dot\phi})}{(s + \alpha)\,(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad \text{(T.F.)}$$

$$K_\phi/K_{\dot\phi} = 1.52$$

$$\Phi_{L_{DIST}}(s) = \frac{2\omega_i\,\sigma_{L_{DIST}}^2}{s^2 + \omega_i^2} \quad \text{(INPUT)}$$

$$\overline{L_C^2} = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} \frac{L_C}{L_{DIST}}(s)\,\frac{L_C}{L_{DIST}}(-s)\,\Phi_{L_{DIST}}(s)\,ds = I\chi\overline{\ddot\phi_C^2}$$

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Figure 9 Roll Control Power Equations

ROLL CONTROL POWER FOR TRIMMING IN A CROSSWIND

OGE

SIDEFORCE – $\ddot{Y}_{CW} + g\,\phi_{TRIM} = 0 \longrightarrow \ddot{Y}_{CW} = \frac{Y_v\, v_{CW}}{m}$

ROLL – $I_X\,\ddot{\phi}_{CW} + L_{C_{OGE}} = 0 \longrightarrow \ddot{\phi}_{CW} = \frac{L_v\, v_{CW}}{I_X}$

IGE

SIDEFORCE – $\ddot{Y}_{CW} + g\,\phi_{TRIM} = 0$

ROLL – $I_X\,\ddot{\phi}_{CW} + L_{C_{IGE}} + L_\phi\,\phi_{TRIM} = 0$

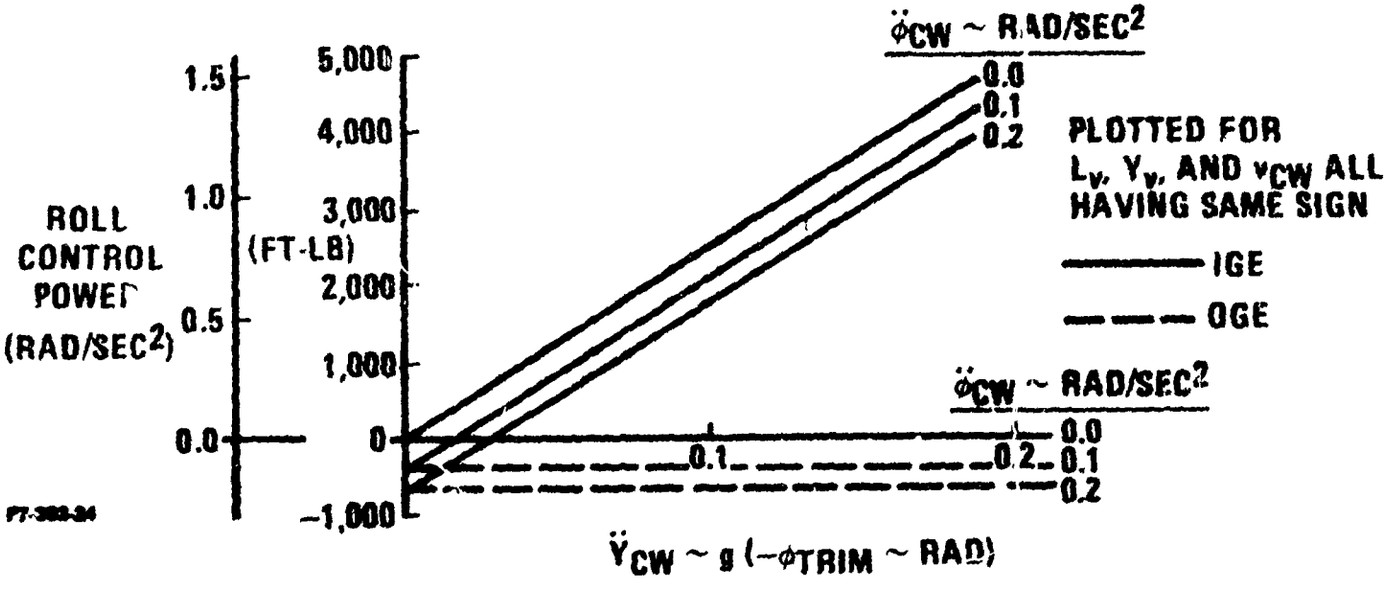


Figure 10 Roll Control Power for Trimming in a Crosswind

ROLL CONTROL POWER REQUIREMENTS

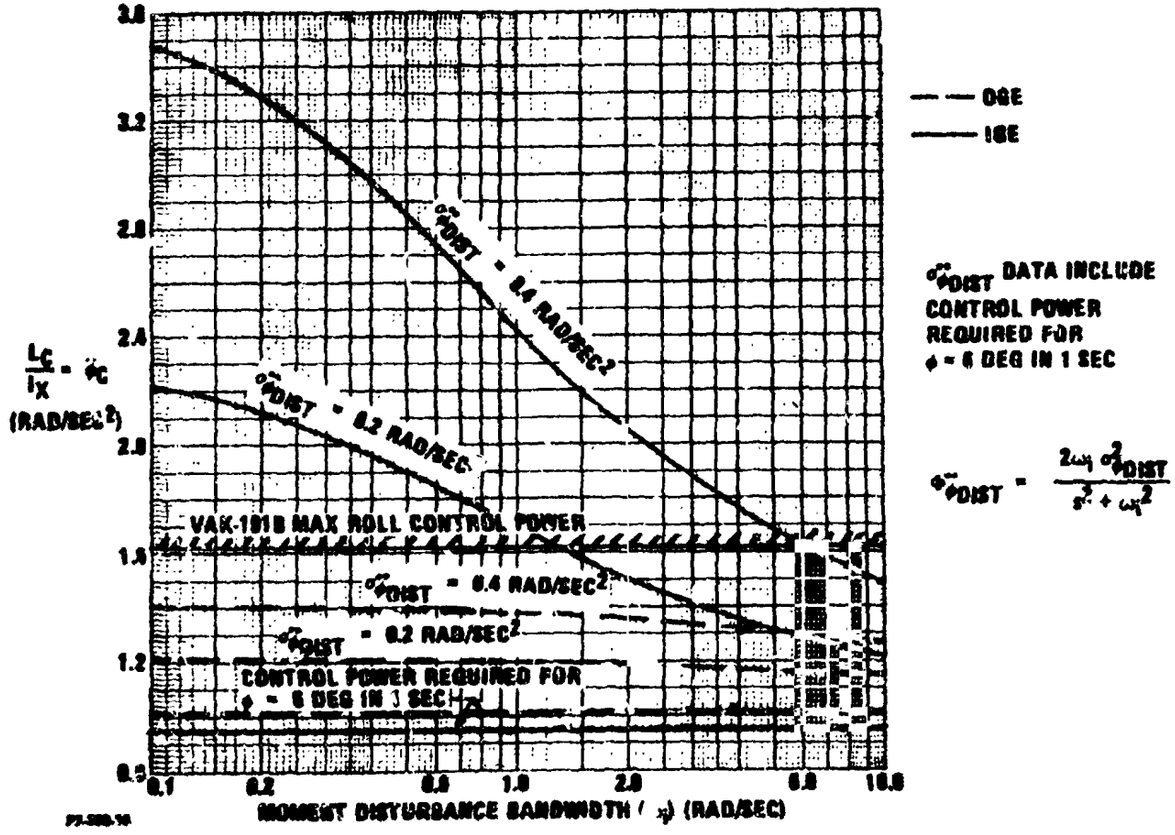
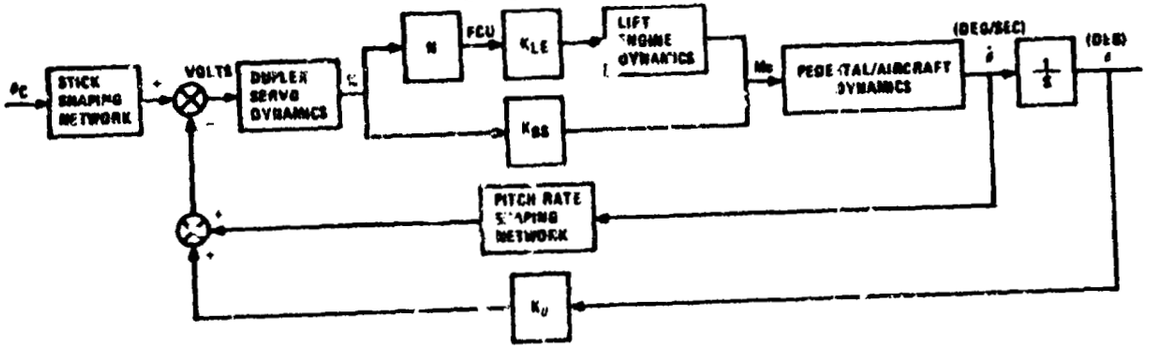


Figure 11 Roll Control Power Requirements

APPENDIX - Figures Summarizing Analysis of the VAK-191B Pitch Frequency Response Data and Longitudinal Flying Qualities in the OGE/IGE Transition

VAK-191B PITCH CONTROL SYSTEM
VTOL MODE



G_{PA} = PEDESTAL/AIRCRAFT DYNAMICS

$$= \frac{0.0043e^{-0.04s}}{\frac{s^2}{9.5^2} + \frac{2(0.5)}{9.5}s + 1} \text{ DEG/SEC/FT-LB}$$

N = DESCRIBING FUNCTION FOR THRUST MODULATION

G_{ST} = STICK SHAPING NETWORK

$$= \frac{0.87(1.199s + 1)}{(1.65s + 1)} \text{ VOLTS/DEG}$$

G_{DS} = DUPLEX SERVO DYNAMICS

$$= \frac{11.63}{\frac{s^2}{23.82^2} + \frac{2(0.89)}{23.82}s + 1} \text{ \%/VOLTS}$$

$G_{\dot{\theta}}$ = PITCH RATE SHAPING NETWORK

$$= \frac{0.81(0.879s + 1)}{(0.832s + 1)} \text{ VOLTS/DEG/SEC}$$

K_{θ} = PITCH ANGLE FEEDBACK = 0.87 VOLTS/DEG

K_{LE} = LIFT ENGINE GAIN = 550.6 FT-LB/DEG FCU

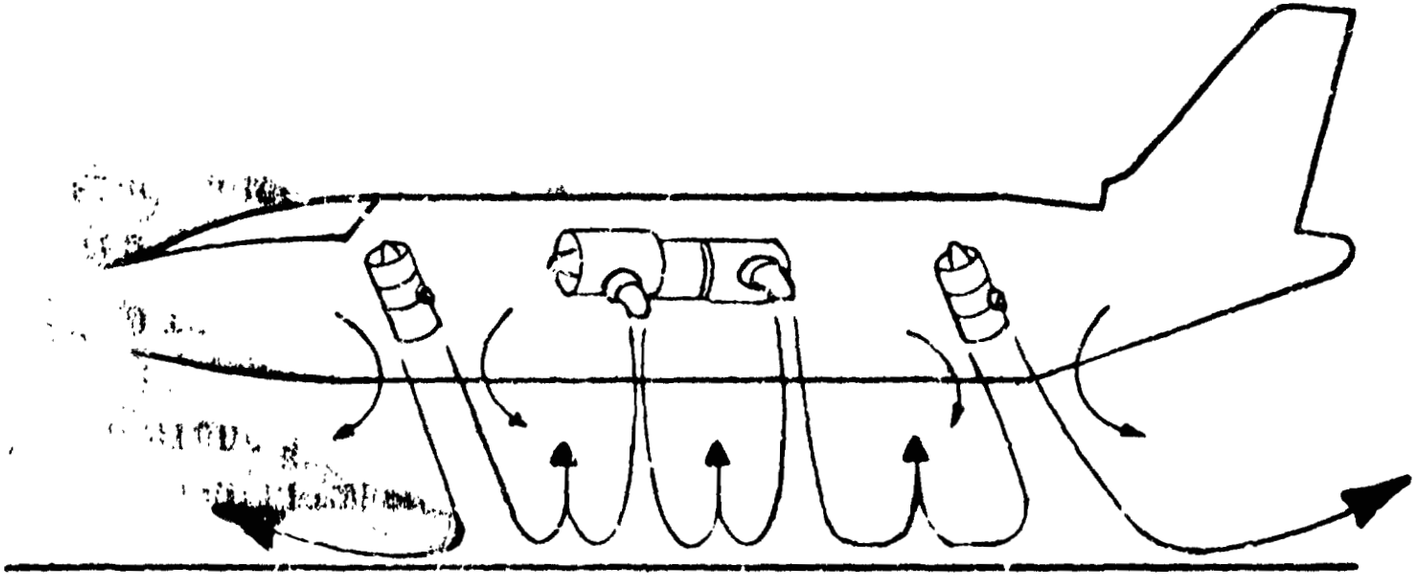
K_{BS} = BLEED SYSTEM GAIN = 236.8 FT-LB/%

G_{LE} = LIFT ENGINE DYNAMICS

$$= \frac{1}{0.5s + 1} \text{ OR } \frac{1}{0.3s + 1}$$

VAK-191B FOUNTAIN CONFIGURATION

SIDE VIEW



AIRCRAFT/PEDESTAL PITCH MODEL DEVELOPMENT

- **OBSERVED –**
  1. PHASE LAG BETWEEN $\dot{\theta}$ AND $\delta_{DS} < 90°$ AT LOW ω AND $> 90°$ AT HIGH ω
  2. MAGNITUDE OF $\dot{\theta}/\delta_{DS}$ FOLLOWS $K_{BS}/I_Y s$ AT HIGH ω BUT NOT AT LOW ω
  3. VAK-191B SHOULD EXHIBIT STABLE PITCH MOMENT IGE PROPORTIONAL TO θ
  4. DEAD TIME IN $\dot{\theta}$ FOLLOWING δ_{DS} MOTION DURING PITCH STEP
- **POSTULATED –**
  1. SECOND ORDER MODEL WITH θ AND $\dot{\theta}$ FEEDBACKS:

$$I_Y \ddot{\theta} = K_{BS}\,\delta_{BS} + M_{\dot{\theta}}\,\dot{\theta} + M_\theta\,\theta$$

$$\frac{\dot{\theta}}{\delta_{DS}} = \frac{-K_{BS}/M_\theta}{\frac{-I_Y}{M_\theta}s^2 + \frac{M_{\dot{\theta}}}{M_\theta}s + 1}$$

$M_\theta < 0$

$M_{\dot{\theta}} < 0$

  2. DEAD TIME AND/OR HIGHER FREQUENCY EFFECTS $-e^{-Ts} \rightarrow T > 0$
- **FITTED DATA –**

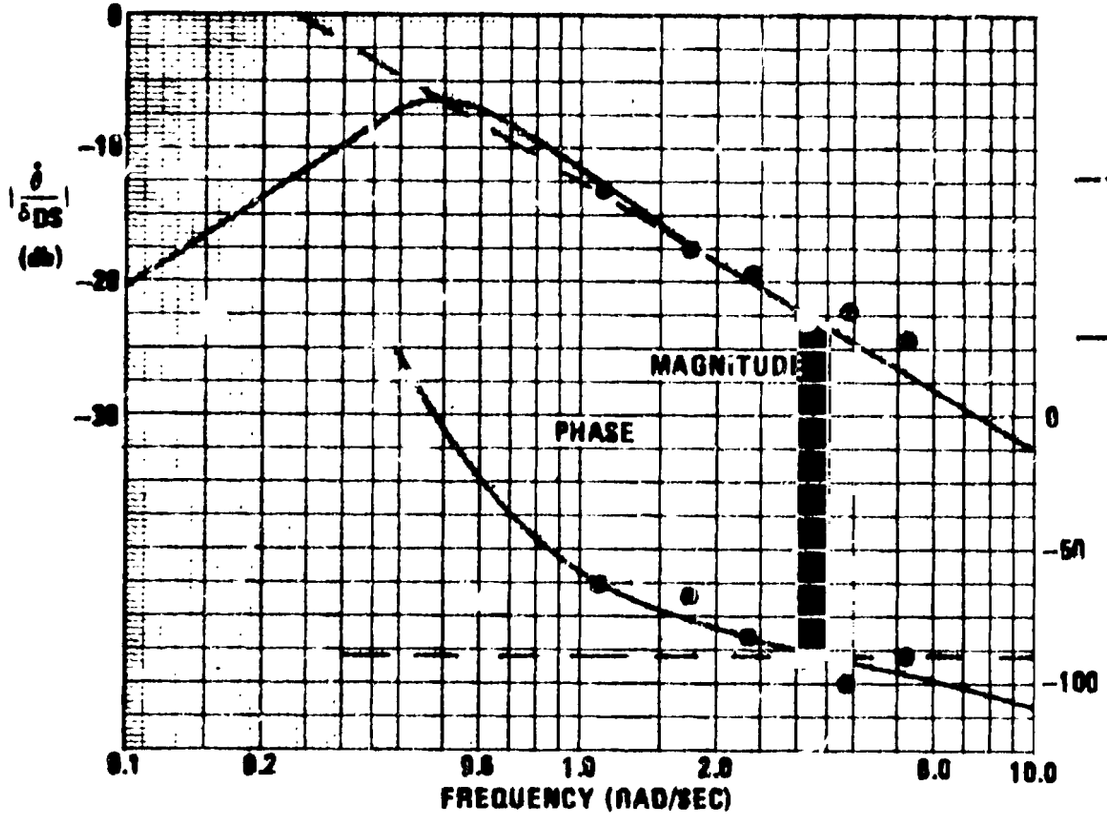
$$\frac{\dot{\theta}}{\delta_{DS}} = \frac{0.95e^{-0.04s}}{\left(\frac{s^2}{0.5^2} + \frac{2\,(0.5)}{0.5}s + 1\right)}$$

$M_\theta = -250$ FT-LB/DEG

$M_{\dot{\theta}} = -500$ FT-LB/DEG/SEC

$I_Y = 56{,}800$ SLUG FT^2

AIRCRAFT/PEDESTAL $\dot{\theta}/\delta_{DS}$ FREQUENCY RESPONSE



◉ ACTUAL DATA
PEDESTAL TEST
1.239

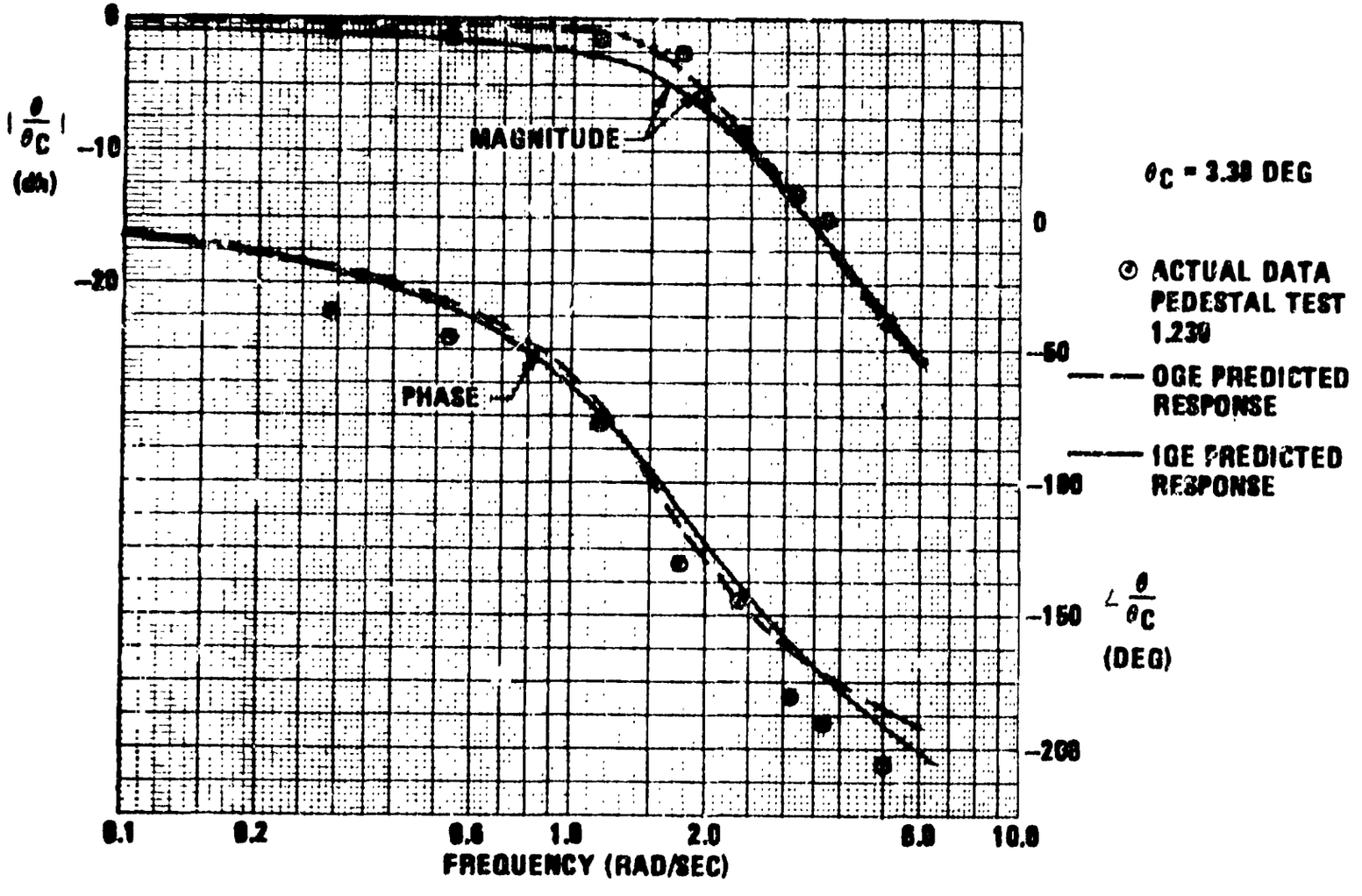
- - - - OGE PREDICTED RESPONSE

$$\left[\frac{\dot{\theta}}{\delta_{DS}} = \frac{K_{BS}}{I_Y S} = \frac{0.237}{S}\right]$$

——— IGE PREDICTED RESPONSE

$$\left[\frac{\dot{\theta}}{\delta_{DS}} = \frac{0.55 e^{-0.04 s}}{\frac{s^2}{0.5^2} + \frac{2(0.5)}{0.5} s + 1}\right]$$

CLOSED LOOP θ/θ_C FREQUENCY RESPONSE



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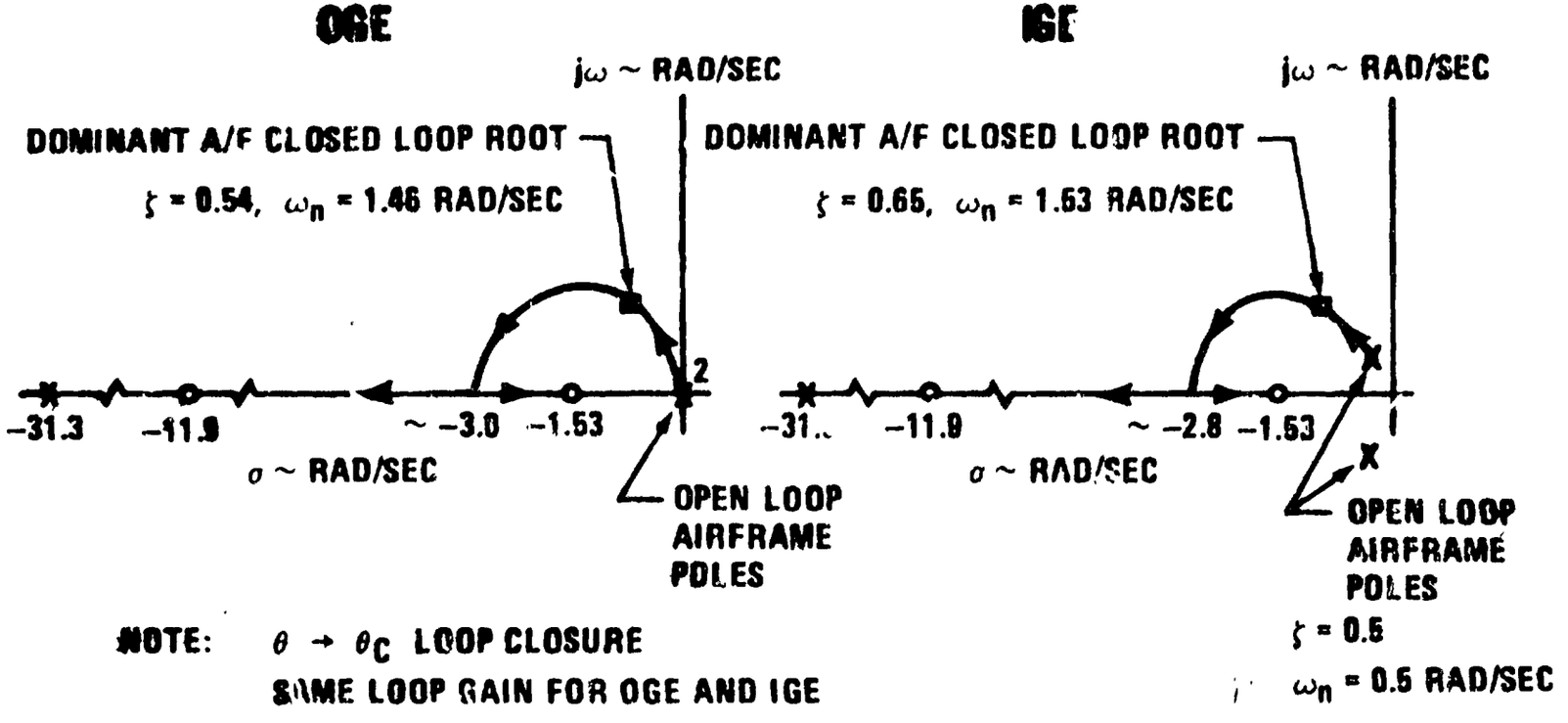
VAK-191B FREQUENCY RESPONSE SUMMARY

- STABLE PITCH FEEDBACKS
  - UNEXPECTED $M_{\dot{\theta}}$ = --500 FT-LB/DEG/SEC
  - M_{θ} = --250 FT-LB/DEG
- UNSTABLE ROLL FEEDBACK
  - L_{ϕ} = 450 FT-LB/DEG
- GOOD CORRELATION WITH MEASURED DATA USING SIMPLE MODELS
- IGE FEEDBACKS IMPLY CHANGES IN
  - SYSTEM DYNAMICS
  - PILOT COMPENSATION/WORKLOAD
  - CONTROL POWER REQUIREMENTS
  - STATION-KEEPING STABILITY
- WHEN TRANSITIONING FROM OGE TO IGE OR VICE VERSA

DIFFERENCE IN VAK-191B CONTROLLED ELEMENT CHARACTERISTICS IN GROUND PROXIMITY

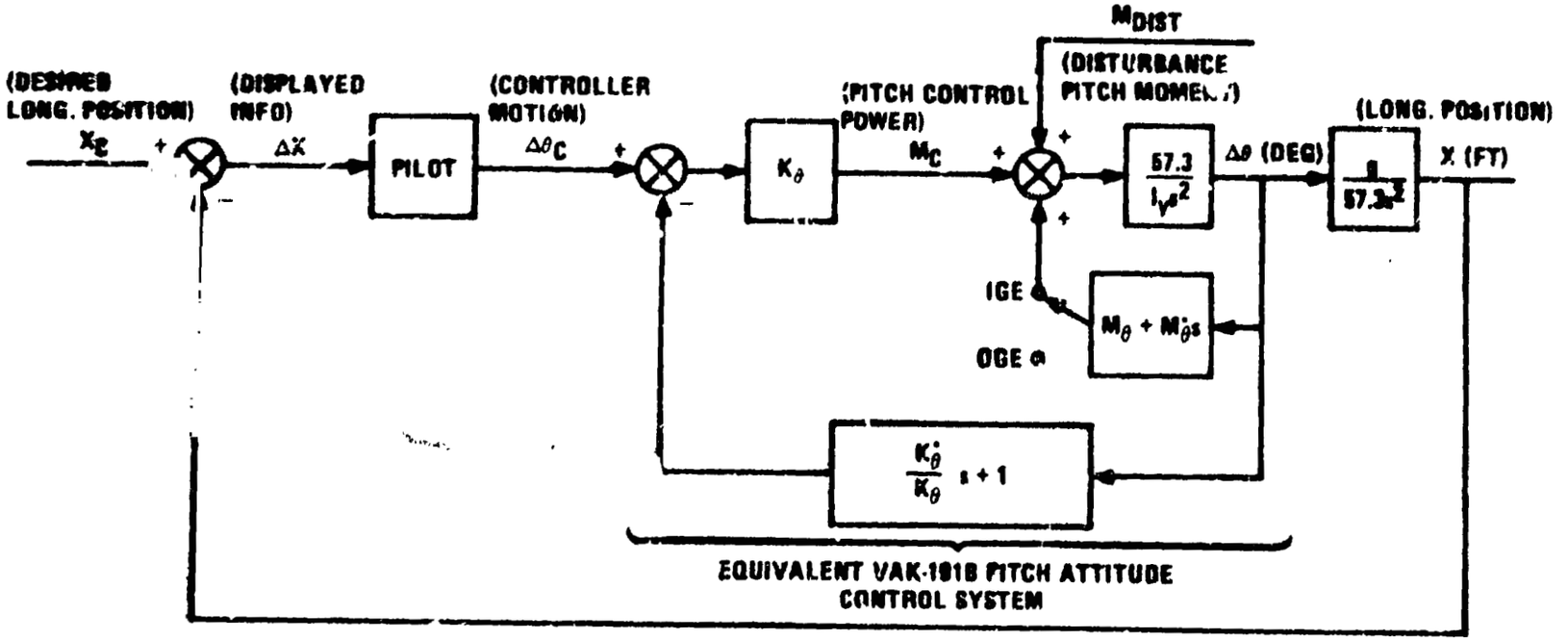
ROOT LOCUS COMPARISON OF PITCH ATTITUDE CONTROL



NOTE: $\theta \rightarrow \theta_C$ LOOP CLOSURE

SAME LOOP GAIN FOR OGE AND IGE

MODEL OF VAK-191B LONGITUDINAL POSITION CONTROL IN HOVER



CONTROL SYSTEM GAINS

K_θ = 2131.8 FT-LB/DEG

$K_{\dot\theta}$ = 1674.8 FT-LB/DEG/SEC

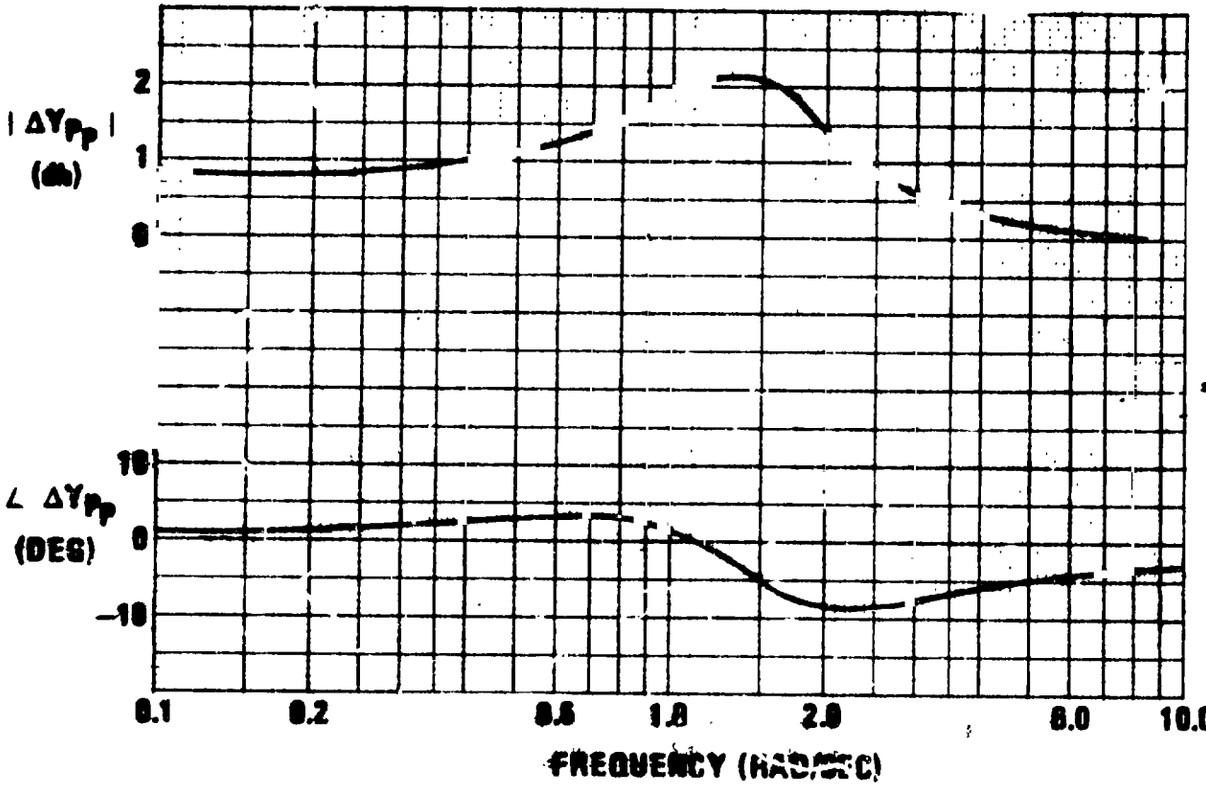
IGE FEEDBACKS

M_θ = −250 FT-LB/DEG

$M_{\dot\theta}$ = −580 FT-LB/DEG/SEC

I_y = 56,000 SLUG-FT^2

PILOT COMPENSATION IN PITCH FOR OGE/IGE TRANSITION



$$\Delta Y_{P_p} = \frac{\left(\frac{\theta}{\theta_C}\right)_{OGE}}{\left(\frac{\theta}{\theta_C}\right)_{IGE}}$$

= PILOT COMPENSATION REQUIRED FOR TRANSITIONING FROM OGE TO IGE TO MAINTAIN CONSTANT LONGITUDINAL POSITIONING PERFORMANCE

P7-3B9-21

PITCH CONTROL POWER EQUATIONS

C.P. FOR MANEUVERING

$$\frac{\theta}{M_C}(s) = \frac{8.001}{s^2 + 2\zeta\omega_n s + \omega_n^2} \text{(T.F.)}$$

$$M_C = \frac{M_{MAN}}{s} \text{ (INPUT)}$$

$$\theta(t) = M_{MAN}\mathcal{L}^{-1}\left[\frac{1}{s}\frac{\theta}{M_C}(s)\right]$$

$$M_{MAN} \quad \theta(1) \Big/ \left[\mathcal{L}^{-1}\left[\frac{1}{s}\frac{\theta}{M_C}(s)\right]\right]_{t=1}$$

$$\omega_n = \begin{cases} 1.46 & \text{OGE} \\ 1.53 & \text{IGE} \end{cases}$$

$$\zeta = \begin{cases} 0.54 & \text{OGE} \\ 0.66 & \text{IGE} \end{cases}$$

C.P. FOR CONTROLLING DISTURBANCES

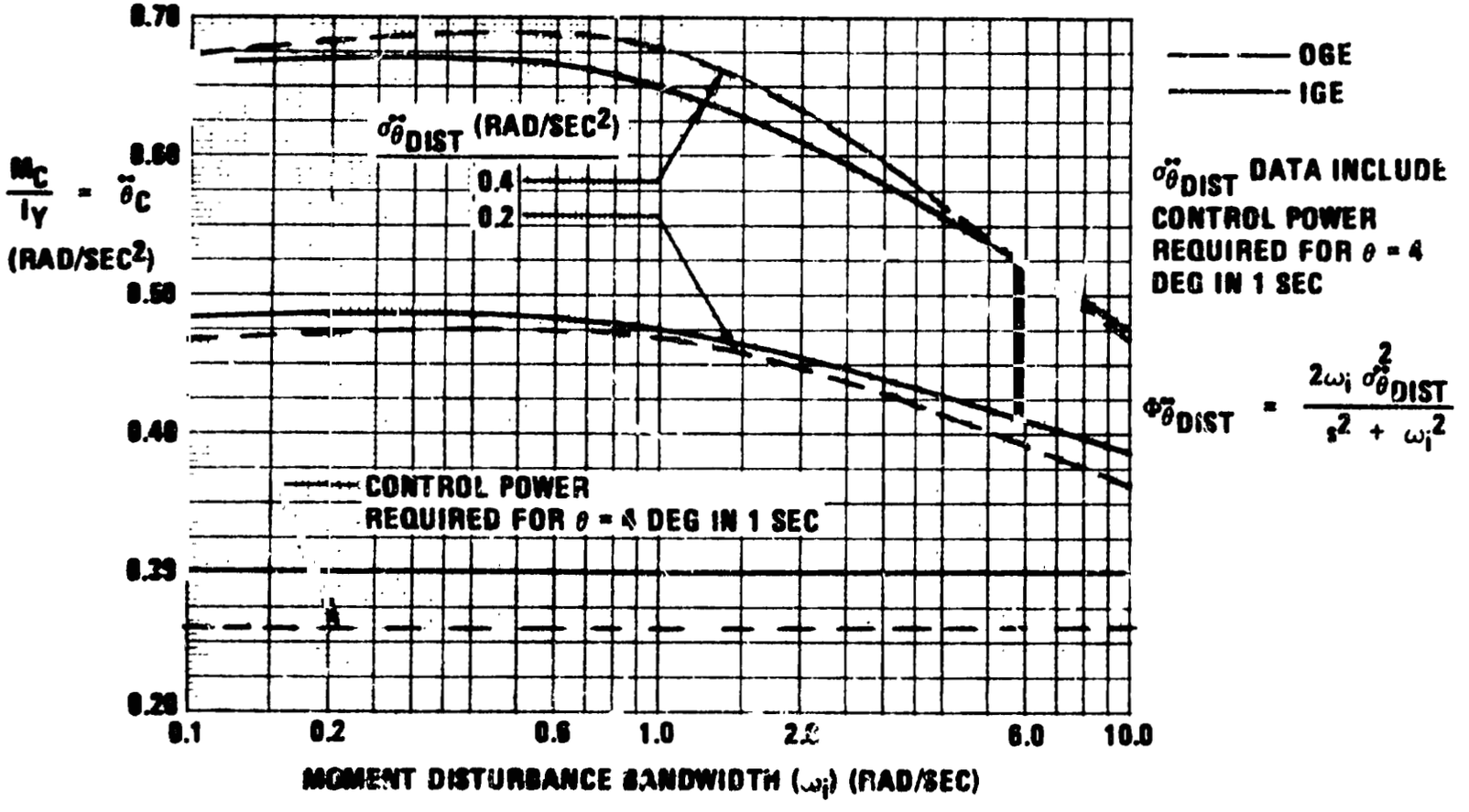
$$\frac{M_C}{M_{DIST}}(s) = \frac{1.58\,(s + K_\theta / K_{\dot\theta})}{s^2 + 2\zeta\omega_n s + \omega_n^2} \text{ (T.F.)}$$

$K_\theta / K_{\dot\theta} = 1.35$

$$\Phi_{M_{DIST}}(s) = \frac{2\omega_i \sigma_{M_{DIST}}^2}{s^2 + \omega_i^2} \text{ (INPUT)}$$

$$\overline{M_C^2} = \frac{1}{2\pi j}\int_{j\infty}^{j\infty} \frac{M_C}{M_{DIST}}(s)\,\frac{M_C}{M_{DIST}}(-s)\,\Phi_{M_{DIST}}(s)\,ds = I_Y\,\overline{\ddot\theta_C^2}$$

PITCH CONTROL POWER REQUIREMENTS



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DISCUSSION

Henry Kelley: In your discussion about the unstable rolling moment in ground effect as a function of bank angle, how did you measure that moment?

Fortenbaugh: Through the frequency response data. I had to assume that much to get it to match the data.

Kelley: From the pedestal data?

Fortenbaugh: Yes.

Kelley: How did you know that the source of the moment was, in fact, due to the jet efflux bouncing off the ground instead of from other sources?

Fortenbaugh: I don't care where it came from; it's there. It could have been sucked under the wing, and it could also have been the fountain effect. Possibly it's both. In any event, it was there and was something that we had to contend with in the airplane.

Kelley: Of the tests made in the past, it has been noted or suggested that this could be a possibility for developing destabilizing moments by V/STOL aircraft when in ground effect.

Fortenbaugh: Well, in this case, we were able to qualify the results from the frequency response data. Which kind of says that the pedestal tests were nice to have.

Anon: How far in ground (effect) was that measured?

Fortenbaugh: Bob, I don't remember the measurements.

Robert Traskos: It was about 0.7 H over V, which corresponded to a height of 11 feet above the ground.

Anon: And what kind of speed?

Fortenbaugh and Traskos: Zero.

Traskos: In fact, although we weren't able to show it on the slide, the pedestal was a static rig that was moveable in pitch, roll and yaw.

Ronald Hess: Bob, was there any data to indicate that the pilot was actually generating a second order lead?

Fortenbaugh: We'd need more data than we had.

Hess: In other words, they have hovered in ground effect.

Fortenbaugh: I didn't say that the pilot generated that. I said that to maintain the same performance in the outer loop, he would have had to generate that. I don't know whether he did or not. I don't think he did. Eric..

Erich Baitis: Did I understand you correctly to say that if you were going to stabilize in roll, it would require a 700 percent increase in control power?

Fortenbaugh: Well, for this airplane, if you want to do anything in ground effect other than land, I'd say that was a design consideration. We have to recognize that it's there. I think that we have to look into the wind-tunnel procedures to see how we're going to obtain it because our current wind-techniques cannot really predict it with respect to magnitude.

Kelley: Has the VAK-191B been hovering free? Unrestrained?

Traskos: Yes, it has hovered free, unrestrained in ground effect.

Kelley: How does the pilot control it?

Traskos: He essentially stayed out of the loop. The aircraft had a high gain, high authority attitude stabilization system and we found out that it was essentially a hands-off system. Anytime the pilot tried to control position in ground effect, he found himself PIO'ing the airplane with most of the action being about the lateral axis. Anytime he stopped with hands off, the airplane would drift, but without a bank angle problem.

Irving Ashkenas: Was lateral motion and ground effect a significant contributor to this rolling moment?

Traskos: It's primarily attitude. You compare the data of the two-poster type aircraft with the data of the wind-tunnel test and find there is some rolling up of the vortex in the motion, but primarily it's just attitude dependent. The ground effect is very sensitive to small changes in attitude and height. It's a combined height-attitude relationship.

Anon: Do they have wind-tunnel models of the VAK-191 that can be tested?

Fortenbaugh: Well, they've made an awful lot of them.

Anon: What I'd like to suggest is that you test the model in the wind tunnel in ground effect at different heights above the ground, and that at each height, you vary bank angle systematically and measure the rolling moment.

Fortenbaugh: I think that would probably be a good idea now that we have an indication of the magnitude of the effect. It might be something to go on, because this is still a very elusive problem in wind-tunnel testing. However, I don't know whether we can trust all the data that we obtain from wind-tunnel tests.

John Williams: Some tests of this nature have been conducted with the Harrier in the U.K. The difficulty has been in simulating the jet exhaust flow, and that truly presents great problems. The effect was certainly demonstrated and some figures were deduced from the tests showing the variability of critical bank angle with height above the ground.

Anon: In the wind-tunnel tests, wouldn't you lose the dynamics that are experienced in flight?

Fortenbaugh: Well, you could measure this, since this is just the slope of the rolling moment vs. bank angle curve. Correct me if I'm wrong, but the VAK-191 wind-tunnel tests missed by 50 percent on the propulsion induced effects relative to the pitch axis. I don't know how they did in roll. Bob, you were more familiar with the pedestal rig than I was.

Traskos: The pedestal rig that these full scale tests were done on was essentially a single post arrangement attached to the airplane at approximately the center of gravity. The pitch axis was free while the roll axis was an offset parallelogram; however, we were rotating the airplane around the centerline of the airplane. Yaw was a swivel about the basic post. As I've said before, the bottom of the aircraft was about 12 feet above the ground.

Anon: What was the magnitude of the bank angle?

Fortenbaugh: I was just going to comment on that. I might mention that the magnitude of the bank angle in the frequency response data which was shown was four degrees. They tried eight degrees, but as you noticed, there was a very high gain at low frequencies. Consequently at the low frequencies, the airplane just rolled over to the side and remained there when they tried to drive it with an eight degree magnitude. If you make a calculation with the math model, it turns out that you're exceeding the roll power of the airplane.

Traskos: I think that probably what added to the credibility of this calculation was the fact that the only way you could get the airplane upright and wings level was to reduce power. Tests were done at a flight RPM on all engines. When it flopped over to about 15 degree bank angle, we could not bring it back up with full control. The only way we could get it back up was to pull the power back. Then the airplane became upright pretty much by itself.

Fortenbaugh: You might note that the middle fountain here (pointing to a slide) was probably broken up by the presence of the pedestal. There were three fountains on the aircraft, so possibly you didn't even have the full effect of the jet efflux. That was only a small part of the effect.

Jack Franklin: Bob, did you have any indication of what the influence of winds, particularly cross winds, might be on the ground effect?

Fortenbaugh: I don't know of any data. Bob may know of some.

Traskos: As for the comparison, Jack, do you mean a comparison between bank angle and cross wind? We weren't allowed to go that far in a cross wind so as to really determine the influence. It was quite large, but we could not make a comparison to show a value such as five knots of wind per degree of bank angle.

Franklin: What the last question leads to is that the airplane, under its present configuration, cannot be flown in a crosswind because one must balance the side force with the bank angle.

Fortenbaugh: At least, not very much crosswind.

Franklin: That would certainly be part of a normal VTOL plan.

Traskos: True. We were limited to five knots of crosswind during vertical takeoffs, to my recollection.

VTOL J.E. Iles: May I make a comment? The practical result of all these big numbers that you're seeing here is that the pilot, in a jet-lift aircraft like this one, doesn't maneuver the airplane in ground effect if he's smart. And the second thing to note is that his gain value around roll attitude is very high. If he has to hover in a crosswind for any reason, he can't be combining that adequately with any relaxation of his roll attitude control. There has to be high gain on it. I think that Mike Deitchman may be able to answer a question about pilot lead. I don't know the data since I haven't had a chance to look at it yet.

Fortenbaugh: Mike, do you want to make a comment on that point?

Mike Deitchman: Not really.

Fortenbaugh: O.K.

Iles: To summarize, the pilot gain has to be at a very high value about the roll axis. You just don't maneuver in ground effect. You set yourself up out of ground effect, and then come through as quickly as possible.